Single PPTA Fiber Tensile Test Under High Strain Rate[1]

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Introduction

Soft body armors are used to protect the human body from projectiles at high velocities, and high strength polymer fibers are typically used as the major component of soft body armors. Among mechanical properties of the high strength polymer fibers, tensile stress-strain behaviors of fibers in the body armor play a key role for ballistic performance. As described in Fig.1, upon ballistic impact, longitudinal and transverse waves rise from the impact region of the body armor. The longitudinal tensile wave propagates through the fiber axis at the sonic velocity of the fiber and the deflection of the fibers in the direction of motion of the projectile occurs subsequently. Understanding material behaviors during the impact event is very important in designing the body armors. Furthermore, the impact speed of a projectile for certifying performance of soft body armor is typically higher than 350 m/s [2], placing the fibers in tension under high rate loading conditions. Despite the high rate loading condition for the fibers in the application, mechanical properties of the fibers have been mostly measured under quasi-static loading conditions which are many orders of magnitude lower in rate compared to real impact conditions.

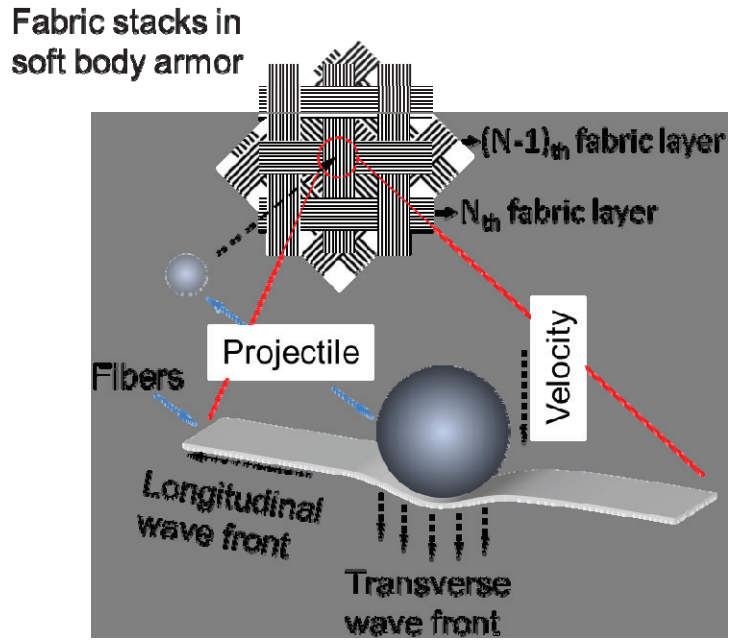

Fig.1. Fiber deformation during ballistic impact

A miniaturized version of a tension Kolsky bar was used to conduct single fiber tensile tests either by gluing a fiber or clamping a fiber on the grips [3, 4]. A comparison study for the glue and clamp methods conducted under quasi-static loading condition clearly demonstrated the higher reproducibility for the clamp method across various fiber lengths [5].

In this study, we used a Kolsky bar to measure tensile properties of single Poly (*p*-phenylene terephthalamide) fibers (PPTA) by directly clamping a fiber on the grips. Fiber tensile properties were then characterized to analyze their distribution using a non-parametric statistical method.

Experiments

Single fiber tensile tests under quasi-static and high strain rate loading

Poly (methyl methacrylate) (PMMA) and rubber were individually used as clamp materials for both tests. For the quasi-static loading shown in Fig.2 (a), a single PPTA fiber was clamped in the grips of a screw-driven machine (FAVIMAT) [6] with approximately 1 mN pretension. The displacement of the actuator was recorded for calculating a strain-to-failure. For high rate loading tests shown in Fig.2 (b), the miniaturized Kolsky bar was used in conjunction with a quartz-piezoelectric load cell (Kistler 9712B5). The estimated uncertainty of the load cell obtained from the manufacture is ± 1.0 %. For measuring the displacement of the Kolsky bar, a thin laser line generated by the laser optical system illuminated a target that is attached to the gripping area of the Kolsky bar, and the intensity of the refocused beam being registered at the photo detector was obtained [7]. The strain (ε) and strain rate ( ) of the fiber specimen for both quasi-static and high rate tests are calculated using the following equations:

– (1)

– (2)

where *d* is the displacement applied to the fiber, *L* is the fiber gauge length, and *v* is the slope of the displacement-time curve. Both tests were carried out at room temperature.

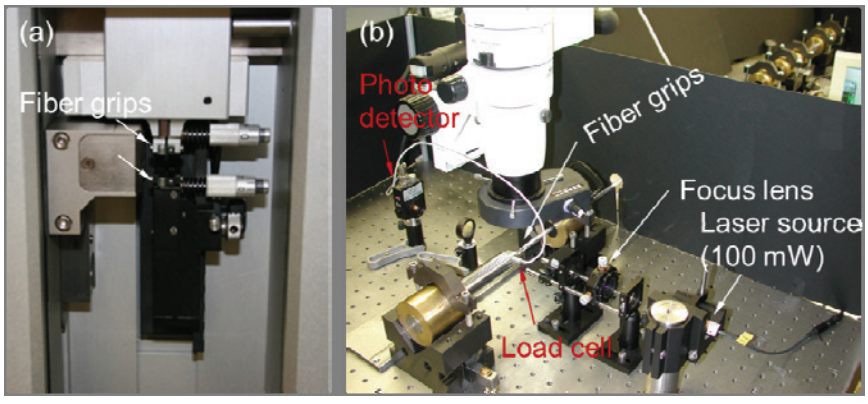

Fig.2 (a) The tensile testing machine for the quasi-static loading and (b) the Kolsky bar set-up with the laser strain measurement system for the high rate loading

Characterization of PMMA and rubber gripping materials

Dynamic mechanical analysis (DMA) was carried out to measure the storage (E□) and loss (E□□) moduli for PMMA and rubber. Specimens for DMA test were deformed in a 3-point bend geometry starting at room temperature and cooled down to -100 °C then heated to 120 °C.

Since a non-uniform contact area between the fiber and grip surfaces can mislead the force-displacement data during single fiber tensile test, surface roughness of the grip materials was examined using an interferemetric optical profiler. The surface profile of the PMMA was measured without any treatment, and the surface profile of the rubber was measured after being coated with a thin gold layer to enhance the reflectivity of the surface.

Experimental Results

The measured glass transition temperatures of both the PMMA and rubber materials were found to be at least 20 °C above room temperature. This implies that both gripping materials are in the glassy state during testing, so a Hookean relationship can be expected for both grips under the tensile load exerted by the fiber during testing. Moreover the root mean square roughness (RMS) values for surfaces of both grips were less than 1 μm, which minimized the relative contribution of the surface roughness on gripping a single fiber.

Single fiber tensile tests using a screw-driven machine and Kolsky bar were carried out under constant strain rates. The strain rate for the tests were 0.0006 s^{-1} for the quasi-static and approximately 900 s^{-1} for the high rate. Typical stress –time curves for the quasi-static and high rate loading tests are shown in Fig. 3. The speeds of the tensile loadings show a linear increment after initial loading regions for both tests. The slopes of the load-time curves were 0.031 GPa/s for the quasi-static and 1.09 x 10^5 GPa/s for the high rate loadings with r^2 □ 0.999, which are highly constant for a majority of the loading period until rupture.

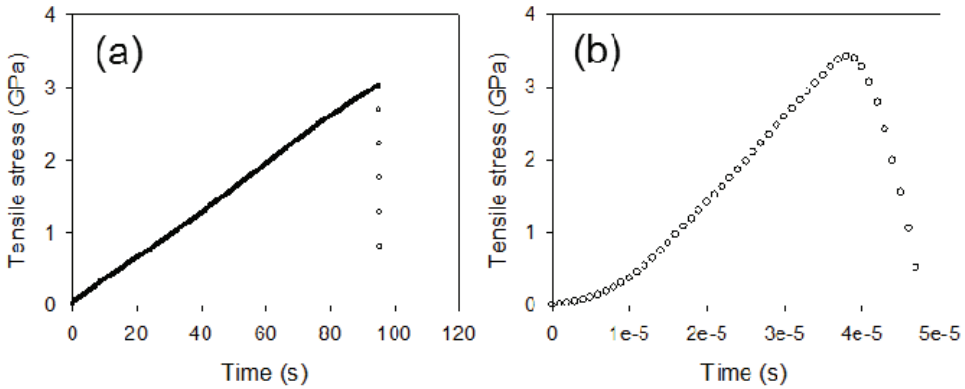

Fig.3 The tensile stress-time curves for the (a) quasi-static and (b) high strain rate tests using single PPTA fibers.

Fiber fracture surfaces showed typically split ends regardless of the loading rates as shown in Fig.4. Apparent split ends in the fracture surface maybe imply either a shear induced fracture initiation from internal fiber structure or crack propagation along PPTA chains initiating from the fiber surface. Considering a possible skin-core structure of PPTA fibers that is known to be vulnerable against external force in the core part [8], the former case may be more plausible.

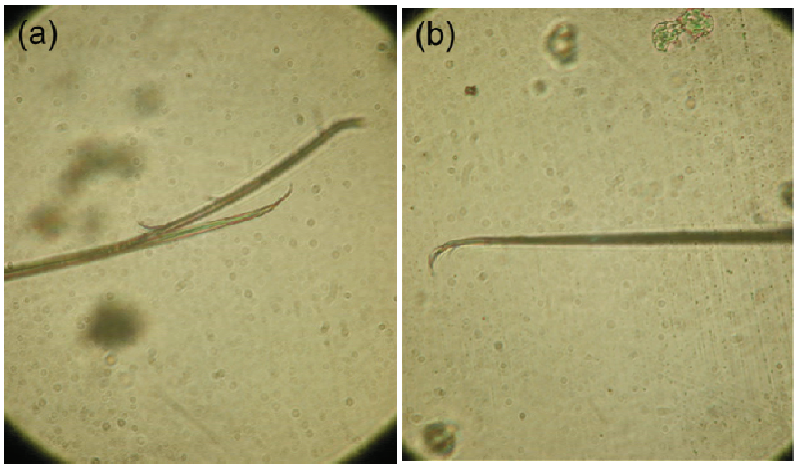

Fig.4 Paired ("a" for one end and "b" for the other end) fiber fracture surfaces of single PPTA fiber tested at the high rate loading.

To model the fracture strengths of the PPTA fibers, the concept of Eyring's energy barrier [9] can be applied to explain fiber fracture as a function of time. In this theory, initial and final equilibrium states are assumed to have the same potential energy in the absence of external forces. This potential energy barrier becomes linearly smaller as external stress is increased. Several fracture models for PPTA fibers adopted this energy barrier concept in conjunction with shear deformations of the secondary bonding with the PPTA chains [9, 10]. Preliminary studies on the rate dependent fiber fracture models using constant stress rates (the slopes of the Fig.3) are carried out and additional results will be discussed in the presentation

Concluding remarks

Single PPTA fiber tensile tests using PMMA and rubber as gripping materials were performed under quasi-static and high rate loading conditions. During the tests, the stress-time responses for the quasi-static and high rate tests were predominately linear until fiber rupture. Future results with strain-time response will help to link stress-strain behaviors for the PPTA fibers as a function of time.

References

1. Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.

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6. Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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